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Development of KURAMA-II and its Operation in Fukushima

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Abstract

A carborne survey system, named as KURAMA (Kyoto University RADiation Mapping system), was developed as a response to the nuclear accident at TEPCO Fukushima Daiichi Nuclear Power Plant in 2011. Now the system has evolved into KURAMA-II, characterized by its compactness, autonomous operation, and acquisition of pulse-height spectrum data. A two-year field test of radiation monitoring by KURAMA-II on local buses, performed by Kyoto University, has successfully proceeded to the phase of official operation by the Fukushima prefectural government, supported by Kyoto University and JAEA (Japan Atomic Energy Agency). An outline and the current status of KURAMA-II, including some results of the continuous monitoring by KURAMA-II on local buses in Fukushima, are introduced.

Keywords:

radiometry, mapping, γ -ray, carborne survey, air dose rate, Fukushima Daiichi nuclear power plant

1. Introduction

The magnitude-9 earthquake in eastern Japan and the following massive tsunami caused a serious nuclear disaster of Fukushima Daiichi nuclear power plant. Serious contamination was caused by radioactive isotopes in Fukushima and surrounding prefectures. KURAMA [1] was developed to overcome the difficulties in radiation surveys and to establish air dose-rate maps during and

27 after the present incident. KURAMA was designed based on consumer products,
28 and enabled a large number of in-vehicle apparatus to be prepared within a
29 short period owing to its high flexibility in the configuration of data-processing
30 hubs or monitoring cars. KURAMA has been successfully applied to various
31 activities in the radiation measurements and the compilation of radiation maps
32 in Fukushima and surrounding areas.

33 As the situation was stabilized, the main interest in measurements moves
34 to the tracking of the radioactive materials that have already been released
35 into the environment surrounding the residential areas. KURAMA is not suit-
36 able for such purposes. Even though KURAMA enables measurements with a
37 large number of monitoring cars over a wide area at one time, it still requires
38 a trained operator and a driver in each monitoring vehicle. This means that a
39 huge amount of resources and efforts will be required once the surveillance is
40 changed into long-term (several tens years) and detailed monitoring in residen-
41 tial areas. Such monitoring can be realized efficiently if vehicles that periodically
42 move around the residential areas, such as city buses, delivery vans or motor-
43 cycles for mail delivery, have compact and full-automated KURAMAs onboard.
44 KURAMA-II is designed for such a purpose.

45 In this paper, a system outline and the development of KURAMA-II as well
46 as the results of continuous monitoring using KURAMA-II will be introduced.

47 2. System outline of KURAMA-II

48 The system outline of KURAMA-II is shown in Fig. 1. KURAMA-II ba-
49 sically stands on the architecture of KURAMA [1], but the in-vehicle part has
50 been totally re-designed. In KURAMA, a notebook PC was used in an in-
51 vehicle unit, but KURAMA-II is based on the CompactRIO series of National
52 Instruments [2] to obtain better toughness, stability and compactness. The
53 3G/GPS module for CompactRIO by SEA [3] provides time and location data
54 as well as connection to a 3G network. The radiation detection part has been
55 replaced from the conventional NaI survey meter to the C12137 detector series

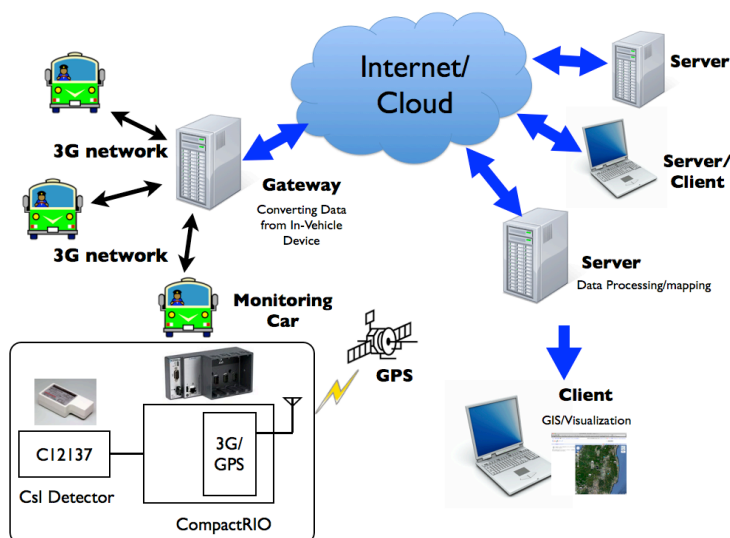


Figure 1: System outline of KURAMA-II. The scheme is basically the same as that of KURAMA, but a gateway server is introduced for the conversion of data chunks from in-vehicle units to data files shared over Dropbox [5] due to no support of Dropbox on CompactRIO.

by Hamamatsu Photonics [4]. This CsI detector series is characterized by its compactness, high efficiency, direct ADC output and USB bus power operation. The direct ADC output enables one to obtain γ -ray pulse height spectra during operation. The specifications of C12137 series used in KURAMA-II are summarized in Table 1. All of the components for the in-vehicle part are placed in a small tool box for a better handling (Fig. 2).

Data communication between C12137 and CompactRIO is achieved using the NI-VISA USB RAW mode. C12137 sends a chunk of binary data every 100 ms, consisting of the number of detected γ -rays, a series of 16-bit ADC data of detected γ -rays, and the temperature inside C12137. A 4096 ch pulse-height spectrum is constructed every 100 ms from the obtained 16-bit ADC data inside CompactRIO. γ -rays whose energy exceeds the upper limit of ADC (around 2.8 MeV) are treated as the upper-limit energy of ADC in the construction of pulse-height spectra.

type	C12137-00	C12137-01
Scintillator	CsI(Tl)	
Scintillator Size	13 × 13 × 20 mm	38 × 38 × 25 mm
Energy Resolution (662 keV)	8 %	8.5 %
Counting Efficiency (662 keV, 0.01 μ Sv/h)	40 cpm	400 cpm
Detecting Device	MPPC	

Table 1: Specification of the C12137 Series [4] used for KURAMA-II. Two types of C12137 series are used, depending on the measurement conditions, such as the expected range of air dose rate.



Figure 2: In-vehicle part of KURAMA-II. The components are placed in a small tool box (34.5 cm × 17.5 cm × 19.5 cm) for the better handling. This tool box is made of 1 cm thick balsa wood plates covered with thin aluminum sheets, and no effective shielding towards typical γ -rays in environment.

70 In KURAMA-II, the air dose rate is obtained from the pulse-height spec-
71 trum by using spectrum-dose conversion operators, the so-called $G(E)$ function
72 method [6][7]. In this method, the air dose rate is directly obtained from the
73 pulse-height spectrum without any spectrum analysis of the complex spectrum
74 of the environmental γ -rays. In the $G(E)$ function method, the total dose D
75 under the existence of a mixed flux of γ -ray with different energies $E_0, E_1, E_2,$
76 $\dots (\phi(E_0), \phi(E_1), \phi(E_2) \dots)$ is given as

$$\begin{aligned} D &= \sum_{i=0} \phi(E_i) h(E_i) \\ &= \sum_{i=0} \int_0^{\infty} \phi(E_i) n(E, E_i) G(E) dE \\ &= \int_0^{\infty} \sum_{i=0} \phi(E_i) n(E, E_i) G(E) dE \\ &= \int_0^{\infty} N(E) G(E) dE, \end{aligned} \quad (1)$$

77 under the assumption of the existence of a weighting function, $G(E)$, satisfying
78 the following integral equation:

$$h(E_0) = \int_0^{\infty} n(E, E_0) G(E) dE, \quad (2)$$

79 where $h(E_0)$ is the conversion coefficient for γ -rays of monochromatic energy
80 E_0 , and $n(E, E_0)$ is the response function of the detector, $N(E)$ is the measured
81 pulse-height spectrum, respectively.

82 The Japanese government recommends the ambient dose equivalent, $H^*(10)$,
83 as the operational quantity of area monitoring. This time, $G(E)$ functions for
84 $H^*(10)$ were determined by the Japan Atomic Energy Agency (JAEA) group
85 for C12137-00 and C12137-01 (Fig. 3). Details concerning the determination
86 of these $G(E)$ functions and the characteristics of KURAMA-II on radiation
87 detection are available in ref. [8].

88 KURAMA-II has a built-in function to observe a photo peak in the pulse-
89 height spectrum, since the gain stability of the detector is directly connected

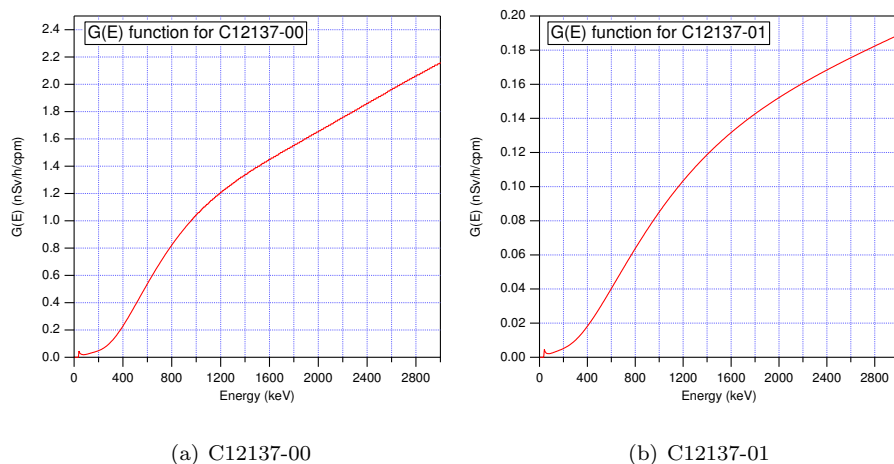


Figure 3: $G(E)$ functions for (a) C12137-00 and (b) C12137-01 calculated by the JAEA group [8].

90 to the stability and reliability of the obtained air dose rate. The 796 keV peak
91 of ^{134}Cs , which is typically observed as a well isolated peak in the pulse-height
92 spectrum of Fukushima area, is used to monitor the gain shift during operation.
93 Up to now, the peak drift is at most 3% throughout the operation for one year.
94 This corresponds to 5% of the drift at most in the air dose rate, one-third
95 of the tolerance for typical portable survey meters used for the air dose rate
96 measurements in Fukushima.

97 The air dose rate and the pulse-height spectrum for each measurement point
98 are collected in the current KURAMA-II scheme. A simple file-transfer proto-
99 col based on RESTful was developed for KURAMA-II, since Dropbox doesn't
100 currently support VxWorks, the operating system of CompactRIO.

101 In this protocol, a chunk of data as a timestamped file is produced for every
102 three measuring points. Then, every chunk is transferred to a remote "gateway
103 server" by the POST method. The gateway server returns the name list of
104 chunks that are successfully received. The chunks in CompactRIO will not be
105 deleted unless those names are confirmed in the returned list from the gateway
106 server. Unsent chunks are archived at every one hundred of them as a single zip

file, and these are sent as soon as the network connection is recovered. Timestamped files of the air dose rate and the pulse height spectrum are separately produced. In the case of the air dose rate, Date/Time, location data, the air dose rate, the temperature of the detector, are written into a timestamped text file. Sometimes additional data are also written into this file upon user's request for special purposes. An example of such special data is the air dose rate calculated from the specific energy region, which is requested by one of the user group for their use. The gateway server combines received files to the data file, which is shared by remote servers using a cloud-based file sharing service, Dropbox[5], as was done in original KURAMA. In the case of pulse-height spectrum, the date/time, location data, air dose rate, list of channel numbers and its counts that are non-zero counting are written into a timestamped binary file. The gateway server records the data of the binary files to a SQL database constructed with sqlite3 and spatialite, and the database file is shared over Dropbox. Users can reconstruct the pulse-height spectrum by specifying the time and location on the SQL database (Fig. 4).

3. Operation of KURAMA-II in Fukushima

3.1. Continuous Monitoring by City Buses

Recent applications of the KURAMA series are mainly with KURAMA-II because of its autonomous operation and ease of handling. One of such applications is continuous monitoring with KURAMA-II on city buses (Fig. 5). City buses are suitable for continuous monitoring purpose in residential areas because of their fixed routes in the center of those areas, and their routine operations.

Following the success of a field test in Fukushima city in 2012, the coverage area has been expanded to other major cities in Fukushima, i.e., Koriyama city, Iwaki city, and Aizuwakamatsu city, since the end of December 2012. Four KURAMA-II are assigned to respective cities, and one additional KURAMA-II is assigned to Aizuwakamatsu, mainly for the field tests of prerelease versions of

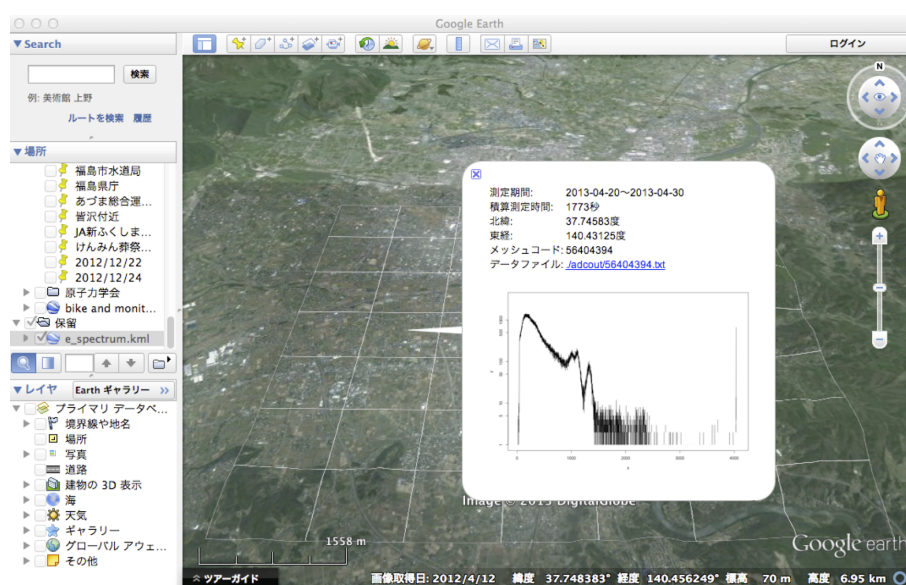


Figure 4: A typical example of the reconstruction of pulse-height spectrum. In this case, the data for a 10 day-period in the spring 2013 and the 1 km × 1 km grid in Fukushima city is reconstructed. Users can reconstruct a pulse-height spectrum based on their interest by using powerful features on the spatial database of sqlite3 + spatialite.



Figure 5: KURAMA-II under a field test on a city bus. An in-vehicle unit is placed on the right side of the rear part in a city bus so that the in-vehicle unit is in the center part of the road.

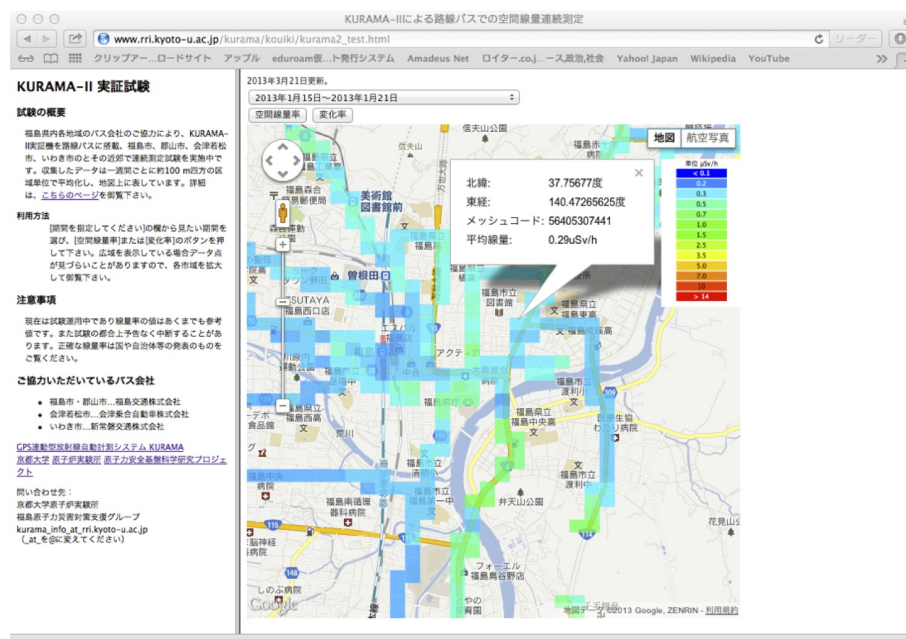


Figure 6: Website for the results of field tests with city buses released from Kyoto University. The results are released to the public on a weekly basis [9].

software. Each KURAMA-II is attached to a certain city bus, and the route of
each city bus is determined by the respective bus operator based on their own
transportation plans. Typically, each local bus completes most of the possible
routes in the respective city within three to five days. The bus routes for respec-
tive cities do not overlap each other. The results of these field tests have been
released to the public through the web sites (Fig. 6) [9] [10]. The results from
this measurement are quite useful for practical purposes, such as confirming the
effect of decontamination in residential areas (Fig. 7).

3.2. Results from the Monitoring by City Buses

Various analyses are on the way to reveal the trends of the air dose rate, the
movement of radioactive materials, and confirmations of the decontamination
effects in the coverage area, thanks to the advantages of city buses, i.e., fixed
routes and daily operations. For example, the change of the air dose rate from

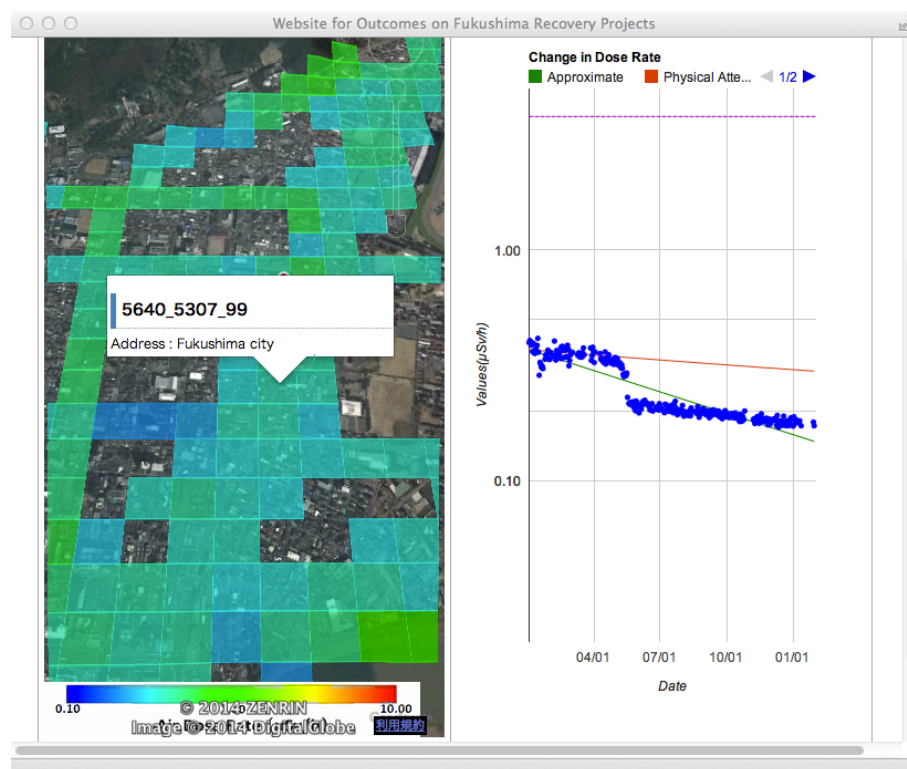


Figure 7: Typical example of the decontamination effect observed through monitoring by KURAMA-II on a local bus. JAEA also releases the monitoring results by KURAMA-II on city buses, including the trends of air dose rates [10]. The grid pointed out in the figure was used as one of the grounds for a large festival in June 2013. The decontamination was performed in May, 2013, prior to the festival. As shown in the graph in this figure, a drastic reduction of air dose rate along with the decontamination was observed, and the decontamination effect has been kept as the reduced air dose rate has been maintained.

149 January 2013 to March 2013 was examined for every $100 \text{ m} \times 100 \text{ m}$ grid cell.
150 In this analysis, the data within every grid cell were averaged for every week,
151 and compared with those in the reference period (from Dec. 20 to 31, 2012).
152 As shown in Fig. 8, the air dose rate is drastically reduced by snow fall. More
153 than a 5% reduction of air dose rate in average was observed in March, even
154 after the snow effect had disappeared. This implies that the snow water caused
155 the movement of radioactive materials in the environment, such as soils or dead
156 leaves, or the migration of radioactive isotopes into deeper soil layers. There
157 are a few grids in which the air dose rate increased compared to the one in
158 the reference period, indicating the possible concentration of the radioactive
159 materials.

160 As for the trend in a one-year period, no significant reduction has been ob-
161 served, except for the effect of snow, but the reduction is found to be generally
162 more rapid than that expected from the physical half lives of Cesium isotopes
163 (Fig. 9). This is also expected to be the result of the movement of radioac-
164 tive materials or the migration of radioactive isotopes into deeper soil layers;
165 however, further studies should be extended, because the reduction was not
166 increased in the rainy seasons in Fukushima (June, July, September, October)
167 when soils and leaves are expected to be washed away or radioactive materials
168 are expected to migrate into deeper soil layers. One possible hypothesis for this
169 reason is that the feed of radioactive materials from the outside of residential
170 areas (such as mountains) also exists in rainy seasons. Therefore, the system-
171 atic tracking of radioactive materials over a wider area should be performed
172 throughout the year.

173 If we look into the details, the difference in these reductions is found between
174 the areas of higher air dose rate and those of lower air dose rate. In Fig.
175 10, the reduction in Fukushima city as a typical example of a higher air dose
176 rate (typically $0.2 \sim 0.5 \mu\text{Sv/h}$) and in Aizuwakamatsu city for a lower air
177 dose rate (typically around $0.1 \mu\text{Sv/h}$). Almost no reduction is observed in
178 Aizuwakamatsu, while the reduction in Fukushima city still continues. This
179 trend is reasonably understood as the difference of the responsible radioactive

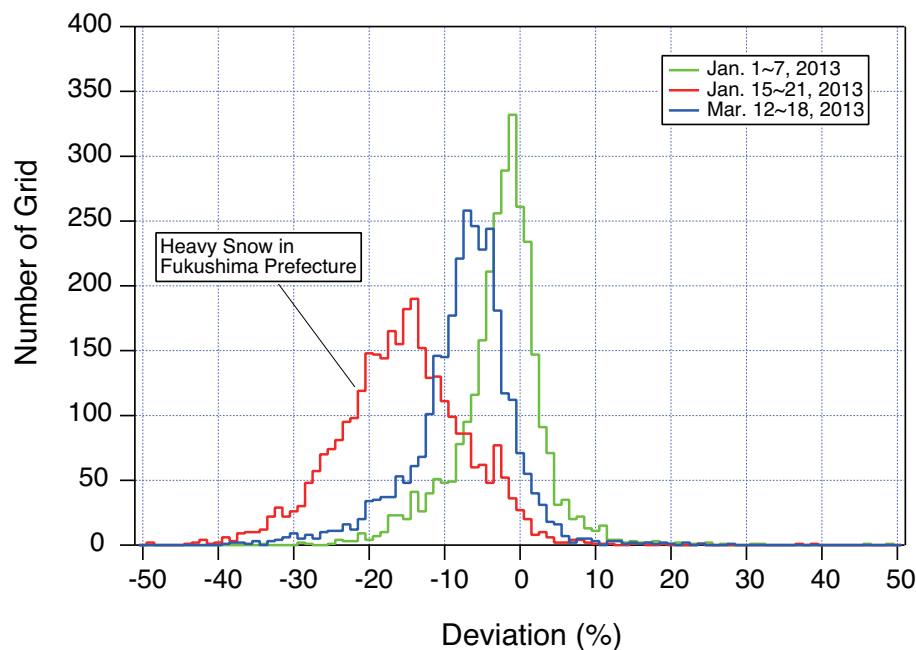


Figure 8: Deviation of the air dose rate in 2013 from the reference period (from Dec. 20 to 31, 2012) in Fukushima monitored by KURAMA-II on city buses. Heavy snow greatly reduced the air dose rate by shielding the radiation.

isotopes for the air dose rate (Fig 11).

3.3. Periodical Survey by Japanese Government

The Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) has introduced KURAMA-II for the periodic carborne surveys in eastern Japan since March 2012 (Fig. 12) [11]. Around one hundred KURAMA-II were deployed to the local municipalities in eastern Japan in each survey. The staff members in each municipality just attach KURAMA-II into a certain place of conventional sedan cars, and drive around their own municipalities. The results of these periodic surveys are released to the public through the web site [12], and numerical data are released to the researchers as a part of the database of environmental monitoring data [13].

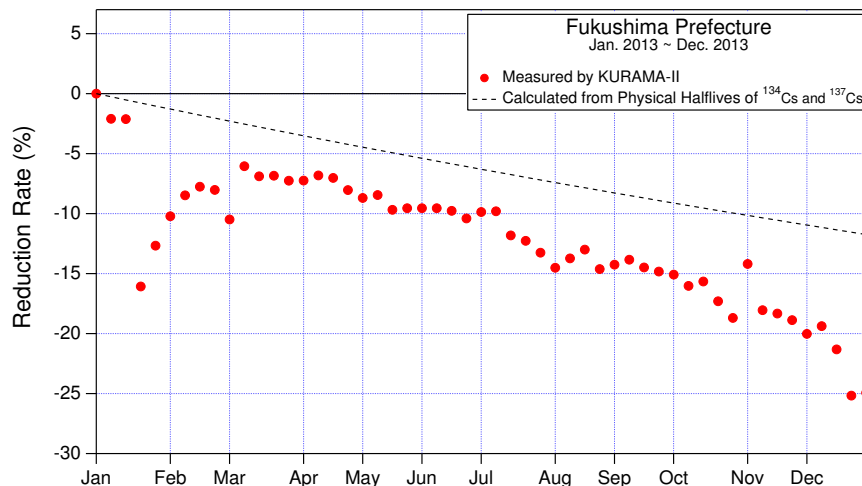


Figure 9: Reduction of the air dose rate in 2013 from the reference period (from Dec. 20 to 31, 2012) in Fukushima monitored by KURAMA-II on city buses. Except for the snow season (from Dec. to Mar.), the reduction is monotonous and more than expected from the physical half-lives of Cesium isotopes.

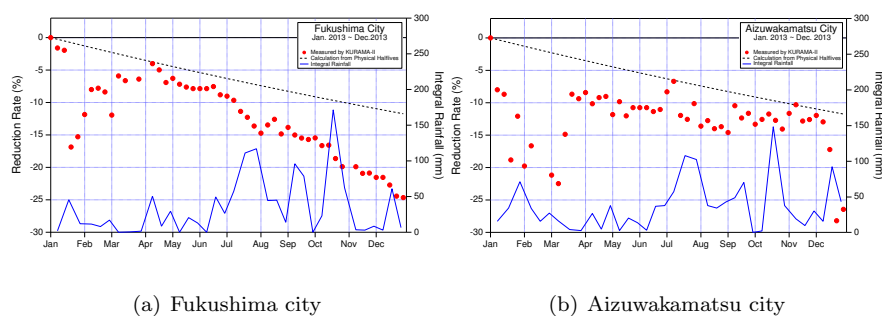


Figure 10: Reduction of the air dose rate from the reference period (from Dec. 20 to 31, 2012) in Fukushima city and Aizuwakamatsu city monitored by KURAMA-II on city buses (red dots) along with the integral rainfall released from the meteorological observatories of respective cities (blue lines). No clear correlation is found between the rain fall and the degree of reduction. Almost no reduction is observed in Aizuwakamatsu city, while that in Fukushima city shows monotonous change, except for the snow season.

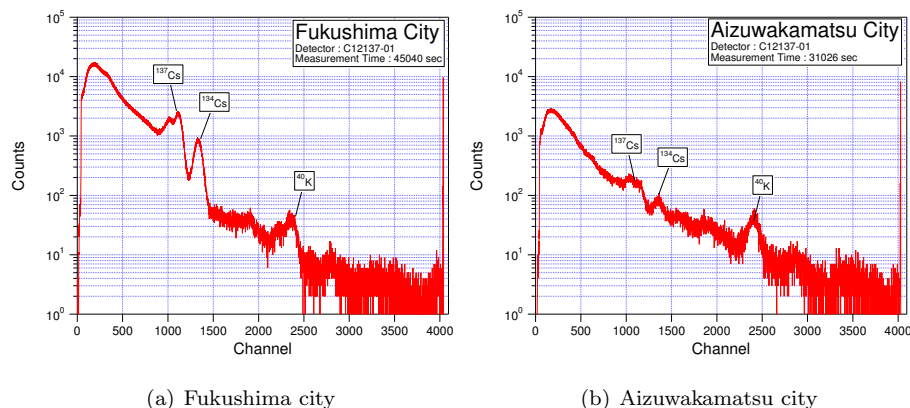


Figure 11: Pulse-height spectra in (a) Fukushima city and (b) Aizuwakamatsu city obtained by KURAMA-II on city buses on 1st Jan. 2014. Typical air dose rates in Fukushima city and Aizuwakamatsu city are $0.2 \sim 0.5 \mu\text{Sv/h}$ and $0.1 \mu\text{Sv/h}$, respectively. In Fukushima city, the dominant component of γ -radiation in environment is Cesium isotopes, while the natural isotopes become competitive to Cesium isotopes in Aizuwakamatsu. The sharp peak at the upper limit of each pulse-height spectrum is due to the folding of pulses more than the upper limit of ADC.

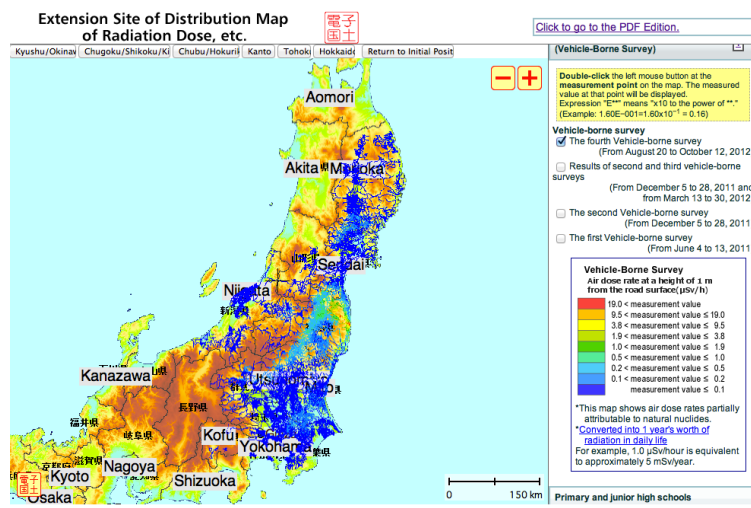


Figure 12: Periodic carborne surveys in the eastern Japan have been performed by MEXT and Nuclear Regulations Authority. The results are available from the interactive web sites [12] [13]. Note that mountain regions are shown in brown in this map.



Figure 13: KURAMA-II on a motorcycle. A CsI detector and other components are separately placed in polycarbonate boxes. The height of the detector is adjusted to 1 m above the ground, so as to meet the standard for the air dose measurement in this accident.

191 4. Conclusion and Future Prospects

192 KURAMA-II has been developed to enable the long-term monitoring of the
193 air dose rate in residential areas. A test operation throughout the year success-
194 fully observed the trends of air dose rates in residential areas, e.g., the shielding
195 effect due to snowfall and reductions due to decontamination activities. Pulse-
196 height spectra obtained by KURAMA-II provide important information concern-
197 ing radioactive nuclides composing the air dose rates in residential areas.
198 No severe troubles, such as the malfunction of a detector, has been found since
199 the field test in Fukushima was expanded to the major cities in 2012. In-vehicle
200 units work quite stable under the severe vibration and the extreme temperature
201 difference in vehicles. Now troubles are rare and minor ones, such as contact
202 failures of power supply line.

203 As of July 2014, the monitoring scheme by city buses had just moved into
204 the phase of official operation by the Fukushima prefectural government with

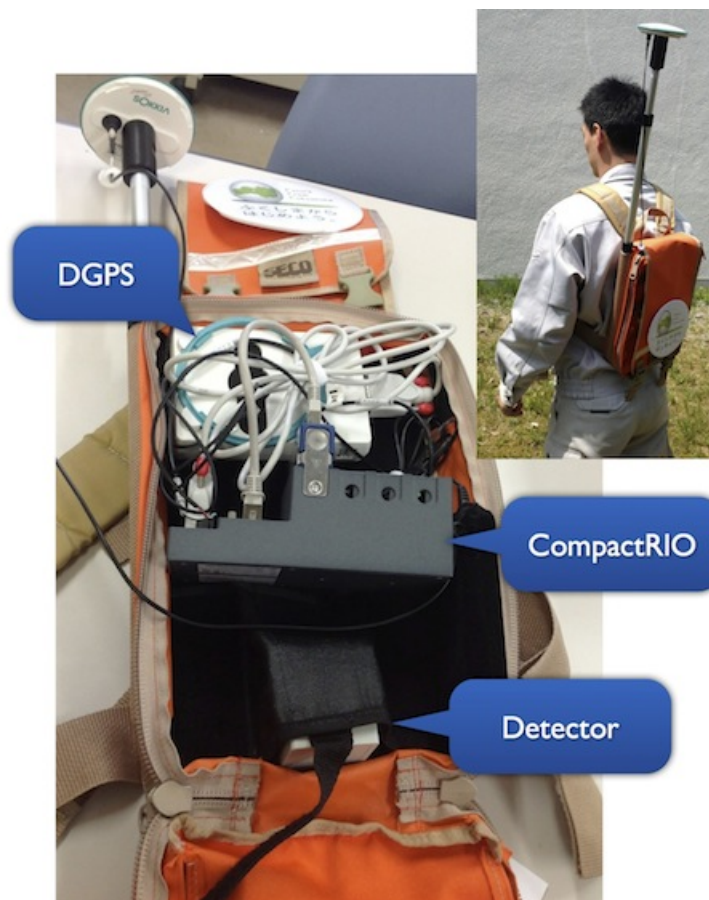


Figure 14: KURAMA-II for the measurement on foot. In this case, a differential GPS (DGPS) unit is used to achieve high accuracy (around 1 m) of positioning sufficient for walking survey.

205 the collaboration of Kyoto University and JAEA. Thirty city buses owned by
206 local bus companies and twenty official cars owned by Fukushima prefecture
207 are continuously operated throughout Fukushima prefecture. Real time data is
208 released to the public on the display system at the public space of a building in
209 Fukushima city, and the summarized results are available on a weekly basis on
210 the web [14].

211 Developments for expanding the application of KURAMA-II are presently on
212 the way. For example, the packaging of KURAMA-II is being arranged for sur-
213 veys by motorcycles or on foot for monitoring, and deployed for measurements
214 in regions where conventional cars can not enter, such as rice fields, forests, and
215 parks (Fig. 13, 14).

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